Solar Energy 139 (2016) 569–580

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Thermal modelling and experimental validation of hot spot in crystalline silicon photovoltaic modules for real outdoor condition

Pramod Rajput [a,*], G.N. Tiwari [a], O.S. Sastry [b]

[a] Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz khas, New Delhi 110016, India
[b] National Institute of Solar Energy, Ministry of New and Renewable Energy, New Delhi 110003, India

A R T I C L E I N F O

Article history:
Received 15 March 2016
Received in revised form 18 September 2016
Accepted 12 October 2016

Keywords:
PV module
Opaque
Semitransparent
IR thermography
Hot spot

A B S T R A C T

In this paper, a mathematical model has been developed to calculate solar cell temperature, hot spot temperature and module efficiency in opaque and semitransparent mono crystalline silicon (sc-Si) PV module. The calculated results have been validated by experimental investigations for both opaque and semitransparent PV modules. Opaque PV module exhibits around 2–3 °C higher temperature in comparison to the semitransparent PV module for one as well as two hot spots. The hot spot temperature decreases with as an increase in the number of hot spots (area of hot spot) in both PV modules. Furthermore, the efficiency of both PV modules has been estimated for one hot spot (opaque 10.41%; semitransparent 10.62%) and two hot spot (opaque 10.41%; semitransparent 10.54%).

1. Introduction

Photovoltaic (PV) modules installation capacity is increasing drastically from the past two decades. In a large scale deployment, reduction in the performance losses is an important concern to make PV module reliable for 20–25 years. Reliability of PV module depends on its conversion efficiency during outdoor exposure. Efficiency of PV modules is affected by different defects, which occurs during outdoor exposure (Ndiaye et al., 2013; Munoz et al., 2011). Thus, there is a need for detection and characterization of such defects in a PV module, from the large string of the PV arrays. Hence the defected PV modules can be easily removed from the string to improve the system performance. The hot spot is one of the common defects which occur in PV modules during long-term outdoor exposure. It mainly occurs due to thermal expansion/contraction of interconnects or solder bonds, shadowing, faulty cell or cells in a string and low shunt resistance cells. When current produced by the faulty cell or shadowing cell is less than the string's current in a PV module (Molenbroek et al., 1991; Garcia et al., 2014). This attributed to increase the solar cell temperature and hence poor performance of PV module Increase in the temperature and area of hot spot creates a cascaded effect on the efficiency of the PV module. Also, insulation resistance has an adverse effect on the performance of PV modules (Lorenzo et al., 2013; Sitthiphol et al., 2016). Generally hot spot in resistive solder bonds decrease more power comparison to hot spot occurs in solar cells (Munoz et al., 2008). In the present study, the active infrared thermography approach has been used for the detection and characterization of hot spot in PV modules.

Hot spot decreases the value of I_{sc} which mainly depends on the shunt resistance; also the performance of the PV module depends on the performance of the one solar cell (Jung et al., 2013; Solorzano and Egido, 2014). Lun et al. (2014) have studied the I–V characteristics of the solar cell in partial shaded condition based on the input parameters i.e. irradiance, temperature and voltage. Fornie's et al. (2014) derived the methods for calculating shunt resistance and compared with the two different modules. The results calculated from the derived methods also compared with the standard methods. Moreton et al. (2015) derived the acceptance and rejection criteria for hot spot on the basis of the irradiance and temperature gradient. They have calculated the temperature gradient by the active infrared thermography.

Active infrared thermography produces images of heat radiation emitted in the infrared spectrum from objects. This is relatively new non-destructive evaluation technique. Non Destructive Testing and Evaluation (NTD & E) by thermography, infrared cameras used to observe how the heat propagates in materials as the material. Invisible defects within the inspected material strongly affect diffusion of heat. Thus, defective areas

* Corresponding author.
E-mail address: pramodraj.rajput3@gmail.com (P. Rajput).

http://dx.doi.org/10.1016/j.solener.2016.10.016
0038-092X/

Nomenclature

A_h	area of hot spot (m^2)
A_m	area of module (m^2)
bca	bottom loss from solar cell to ambient
bha	bottom loss from hot spot solar cell to ambient
C	specific heat (J/kg K)
C_{sab}	total cross – sectional area of busbar (m^2)
C_{sag}	total cross – sectional area of grid line (m^2)
C_{saSi}	total cross – sectional area of Si (m^2)
h_i	heat loss coefficient from bottom (W/m^2 K)
h_o	heat loss coefficient from top (W/m^2)
i	current (A)
$I(t)$	irradiance (W/m^2)
K_g	thermal conductivity (W/m K)
l	length (m)
L_g	thickness of glass (m)
l_h	length (thickness) of the hotspot (m)
l_{tb}	total length of busbar (m)
l_{tg}	total length of gridline (m)
l_{Si}	total length of si (m)
P_{in}	input power (W)
P_o	output power (W)
R	resistance (Ω)
T	Temperature (°C)
tca	top loss from solar cell to ambient
tha	top loss from hot spot solar cell to ambient
T_o	temperature at standard test condition (STC)
U_L	overall heat transfer coefficient (W/m^2 K)
ρ_b	resistivity of busbar (Ω m)
ρ_d	density (solar cell material) (kg/m^3)
ρ_g	resistivity of gridline (Ω m)
ρ_r	resistivity (Ω m)
ρ_{Si}	resistivity of Si (Ω m)

Subscripts

a	ambient
c	solar cell
g	glass
h	hotspot
m	Module

Greek letters

α	absorption factor
τ	transmissivity
β	packing factor
β_o	temperature coefficient of the material
η	efficiency
η_o	solar cell efficiency at standard test condition (STC)

may look cooler or hotter in respect of non defective areas of the sample (Halabe et al., 2007). This difference of temperature caused by non defects or non uniform material is visible through infrared cameras.

Few researchers (Tsanakas et al., 2015; Gupta et al., 2012) have used active infrared thermography for detection of hot spot in PV modules. However, in the present study, methods are different from the past study. In the present analysis a mathematical model has been developed for calculation of hot spot temperature and efficiency in opaque and semitransparent PV module. The theoretical hot spot temperature and efficiency have been compared with experimental value in real outdoor condition in NISE, Gurgaon, India by using active infrared thermography and Solar Amprobe 4000.

In the present study, the hot spot investigation approach of active infrared thermography has been done. In this context, hot spot occurred in sc-Si PV module in real outdoor condition has been detected by an infrared camera.

2. Theory and modelling

2.1. Thermal modelling of hot spot for opaque PV module

In the present study, electro-thermal modelling and simulation has been done for estimating the temperature of hot spot, which has been further compared with experimental results.

The efficiency and temperature of PV module have been calculated using energy balance equations. To write the energy balance equations for PV modules, following assumptions have been considered:

(i) One-dimensional heat conduction.
(ii) The encapsulate ethylene vinyl acetate (EVA) is purely transparent.
(iii) The top and bottom loss coefficients from the hot spot area and non hot spot area assumed to be same.
(iv) Temperature of the non hot spot solar cells assumed to be same.
(v) The measurement time of i^2r loss is assumed to be negligible. The energy balance equation for opaque sc-Si and mc-Si PV module can be written as:

$$\alpha_c\tau_g\beta_c I(t)A_m + \alpha_T\tau_g(1-\beta_c)I(t)A_m = [U_{tca}(T_c - T_a) + U_{bca}(T_c - T_a)](A_m - A_h) + [U_{tha}(T_h - T_a) + U_{bha}(T_h - T_a)]A_h + \eta_c\tau_g\beta_c I(t)(A_m - A_h) \quad (1)$$

The first term on the left hand side shows the total solar radiation received by the solar cells (area covered by the solar cells) and the second term shows the total solar radiation received by the non packing area. The first and second term on the right hand side shows the total thermal energy losses from the non hot spot area and hot spot area of the PV module through top and bottom surface. The last term in the right hand side shows the rate of the electrical energy generated by the non hot spot solar cells.

From Eq. (1), T_c can be written as

$$T_c = \alpha_c\tau_c\beta_c I(t)A_m + \alpha_T\tau_g(1-\beta_c)I(t)A_m + U_L T_a(A_m - A_h) - (U_L T_h - U_L T_a)A_h - \eta_c\tau_g\beta_c I(t)(A_m - A_h)/U_L(A_m - A_h) \quad (2)$$

On the basis of the heat transfer law i^2r losses represented as in hot spot solar cells (Hoyer et al., 2009; Tsanakas et al., 2015).

The i^2r losses are responsible to raise the temperature of the hot spot area more in comparison to non hot spot area

$$P = i^2r = \rho_d C A_h l_h(T_h - T_c)/t \quad (3)$$

where t is the measurement time of i^2r loss from the hot spot solar cell, which less than 10 ms (Kasemann et al., 2009). The i^2r losses lead to the decreases the efficiency of hot spot solar cell in PV modules. Typically, a 10 °C difference causes about 4% power losses for the light hot spot and minimum 18 °C difference causes about 10%